THE PSDF-- COMMERCIAL READINESS FOR COAL POWER--REVISITED

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I. SUMMARY

The Power Systems Development Facility (PSDF) near Wilsonville, Alabama, is a joint project of the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL), Southern Company, and other industrial participants currently including EPRI (formerly the Electric Power Research Institute), Siemens Westinghouse Power Corporation, Kellogg Brown & Root (KBR), and Peabody Energy. The PSDF is an engineering scale demonstration of key components of advanced coal-fired power systems designed at sufficient size to provide data for commercial scale-up.

Operation of the KBR transport reactor at the PSDF, in combination with a high-temperature, high-pressure (HTHP) filter, has shown that it offers many advantages over current gasifiers and combustors that can lead to successful commercialization. These include high carbon conversion, high sulfur capture, a small footprint with a high thermal throughput, and a simple, robust mechanical design.

Southern Company has developed a conceptual commercial plant design and cost estimate for a nominal 300-MW, air-blown Transport Reactor Integrated Gasification (TRIG™) combined cycle power plant based on a General Electric (GE) 7FA gas turbine. This paper is an update of information presented at the DOE Clean Coal and Power Conference in Washington, D. C. on November 19-20, 2001.

The new plant layout, thermal performance, and plant cost for the second-of-a-kind nominal 300-MW TRIG™ plant design is presented. The design is a 1-on-1 arrangement incorporating a single gasifier with a heat recovery steam generator (HRSG) and gas turbine, and a single steam turbine. The projected total plant cost for a greenfield site is $1,385/kW with a lower heating value (LHV) heat rate of 7,680 Btu/kW-hr (44.4 percent efficiency) at average annual ambient conditions of 65°F and 60 percent relative humidity. The HRSG incorporates a unit for the selective catalytic reduction (SCR) of NO_x, and the flue gas is cleaned using a proprietary SCS

flue gas treatment (FGT) process. Projected emissions for SO_2, NO_x, and particulate are below 0.005, 0.05, and 0.0003 lb/MBtu, respectively. In addition, this proprietary FGT unit removes almost all the remaining environmental species of interest, including sulfur trioxide, hydrogen chloride, hydrogen fluoride, ammonia slip from the SCR unit, oxidized and nonoxidized mercury, trace elements, and volatile organic compounds to near their lower detection limits. When built, the TRIG™ plant will be the cleanest, and when adjusted for local conditions, the most efficient coal-based power plant technology in the world.

To illustrate the potential economic advantage over current state-of-the-art power plant technologies, an estimate was prepared for an n^{th}-of-a-kind nominal 600-MW TRIG™ plant design. This design is a 2-on-1 arrangement, incorporating two gasifier trains (each train including a nominal 300-MW gasifier with an HRSG and gas turbine), and a single steam turbine.

II. INTRODUCTION

The PSDF, located near Wilsonville, Alabama, is an engineering scale demonstration of several key components of advanced coal-fired power systems (PSDF web site: "http://psdf.southernco.com/"). The PSDF was designed at a size sufficient to test advanced power systems and components in an integrated fashion and provide data for commercial scale-up.

The PSDF is a joint project of U.S. DOE-NETL, Southern Company, and other industrial participants currently including EPRI, Siemens Westinghouse Power Corporation, KBR, and Peabody Energy. Southern Company is a super-regional energy company with more than 32,000 megawatts of electric generating capacity in the Southeast, and is one of the largest users of coal in the United States, generating more than 22,600 megawatts from this low-cost, domestic fuel source.

Process Systems at the PSDF

A primary purpose of the PSDF is to test particulate control devices for advanced coal-based power systems. Tests are currently being performed on a variety of ceramic and metal filter elements housed in a Siemens Westinghouse HTHP filter vessel. Filters operating in both combustion and gasification environments have been exposed to particulate-laden gases at temperatures from 700 to 1,400°F.

Two separate trains were constructed at the PSDF to supply gas to the HTHP filters: a KBR transport reactor and a Foster Wheeler Advanced Hybrid Pressurized Fluidized Bed Combustion system. These technologies were selected for their flexibility in supplying gases to the HTHP filters and for their potential to be developed into cost-competitive, environmentally acceptable coal-based power plants. The Foster Wheeler combustor was operated for 170 hours on coal in 2000. Because Foster Wheeler has redefined its advanced coal commercial offering, further testing of their system at the PSDF has been cancelled.

Testing of the KBR transport reactor as a combustor has been completed. Testing of the transport reactor as an air-blown gasifier is under way, and results reveal its promise for commercial applications. Initial tests as an oxygen-blown transport gasifier have been carried out and further testing is scheduled for 2003. This paper will review tests of the transport reactor and its HTHP filter and present a study of a commercial design of an air-blown transport gasifier-based power plant.

The transport reactor operates at considerably higher circulation rates, velocities and riser densities than conventional circulating fluidized beds, resulting in higher throughput, better mixing, and higher mass and heat transfer rates. Because of its operating conditions, the transport reactor is well-suited to using high ash, high moisture content coals. Syngas from a transport reactor in gasification mode can be used to fuel a gas turbine or a fuel cell.

A schematic of the transport gasifier is shown in Figure 1. Fuel, limestone, steam, and air or oxygen are combined in the mixing zone with solids recirculated from the standpipe. The gas with entrained solids moves up from the mixing zone into the riser (which has a slightly smaller diameter) and then enters the disengager. The larger particles in the gas are removed by gravity separation in the disengager and then most of the remaining particles are removed in the cyclone. The gas stream exits the cyclone to a gas cooler and then goes to a HTHP filter for final particulate removal. The solids collected by the disengager and cyclone are recycled to the mixing zone through the standpipe and J-leg. When configured as a combustor, the transport reactor also includes a fluidized-bed solids cooler (not shown in Figure 1) which removes heat from the circulating solids before they are returned to the mixing zone.

III. OPERATION AND RESULTS

Combustion Tests

The transport reactor ran in combustion mode for approximately 5,000 hours from 1996 through 1999 at typical operating conditions of 1,625°F and 215 psia. Fuels used included bituminous coals from Alabama, East Kentucky and Illinois, a sub-bituminous coal from the Powder River Basin (PRB) in Wyoming, and petroleum coke from an Alabama refinery. Stable operations were demonstrated for all fuels and sorbents tested.

More than twenty types of filter elements were tested in the HTHP filter during combustion, including monolithic oxide, monolithic silicon carbide, composite, and metal materials. The longest exposure time for individual filters was about 3,300 hours. After transport combustor system commissioning, the HTHP filter was operated at approximately 1,400°F during five test runs. Extensive efforts were made to identify filter element failure mechanisms, evaluate material performance, and improve ash removal system operation. As a result, the reliability of the HTHP filter system was significantly improved.

Although the transport reactor operated successfully as a combustor, the greatest potential for commercial application lies in using it as a gasifier.

Gasification Commissioning Runs

The transport reactor was reconfigured as an air-blown gasifier in 1999 by removing the solids cooler from service and commissioning the atmospheric pressure combustors for the char and syngas [1]. The transport gasifier has operated for over 2,700 hours in gasification mode as of June 2002, including 150 hours of oxygen-blown operation. Fuels tested to date include a PRB sub-bituminous coal and two bituminous coals, an Illinois #6 coal from the Pattiki mine and an Alabama coal from the Calumet mine.

The first gasification commissioning runs were hampered by high filter pressure drops and poor filter cake cleaning due to higher-than-expected solids carryover from the gasifier. The high carryover meant that the HTHP filter char removal system was operating at its maximum capacity and this limited the amount of coal that could be fed to the gasifier. The inefficient solids removal from the syngas also resulted in lower-than-expected solids recirculation rates and carbon conversion.

To increase solids collection efficiency, a loop seal was added beneath the primary cyclone and the disengager barrel was lengthened. These modifications were successful, greatly improving solids collection efficiency and allowing higher solids circulation rates (Figure 2). The reduced carryover lessened the burden on the HTHP filter char removal system and allowed higher coal feed rates. The modification also raised the carbon content in the circulating solids, increasing carbon conversion (Figure 3) and increasing syngas heating value by raising the $CO:CO_2$ ratio.

The final gasification commissioning run was completed in March 2001 after 242 hours of operation. A blend of several PRB coals with Bucyrus limestone from Ohio was used. Gasifier and HTHP filter operations were stable, but the coal feed system experienced problems with fine coal grinds. Based on the experience of this run, several modifications were made to the system. To prevent tar condensation during startup, a coke breeze feed system was implemented that raised the gasifier temperature to 1,600°F before starting coal feed [2].

The char collected by the filter during gasification offers a higher flow resistance than the ash collected during combustion. For the same filter operating conditions this will result in an increased filter pressure drop. To counter this increase, the filter is pulsed cleaned more frequently, typically every 5 minutes compared to every 40 minutes in combustion. For gasification the filter operates at 700°F compared to 1400°F in combustion. This lowers the face velocity to typically 3 feet/min from 5 feet/min, and also helps limit the increase in pressure drop. Monolithic silicon carbide, composite, and metal filter elements were all used during the gasification commissioning runs.

[1] These two pieces of equipment will not be used in a commercial plant, but are used at the PSDF to dispose of the syngas and char.
[2] The startup heater at the PSDF is undersized and difficult to replace. A commercial facility will use a natural gas-fired startup burner rather than a gas-fired burner supplemented by a coke breeze feed system.

Gasification Test Campaigns

The first gasification test campaign was started in July 2001 and continued until September 2001 using PRB sub-bituminous coal. Gasifier and HTHP filter operations were very stable, with the longest period of continuous operation being more than 500 hours. Figure 4 shows gasifier temperature and pressure data from this run. Syngas heating values corrected for heat losses and nitrogen dilution effects [3] were between 100 and 120 Btu/scf (Figure 5), and cold gas efficiencies, with the same corrections, were between 70 and 75 percent. For riser temperatures greater than 1750°F, carbon conversion of over 95 percent was achieved consistently, which is excellent for a fluidized-bed gasifier. Gasifier performance can be improved by adjusting several parameters including using a finer coal grind. Modifications are under way that will allow finer coal to be fed reliably.

The second test campaign was started in December 2001 and completed in April 2002. The main focus was commissioning gasifier modifications in preparation for oxygen-blown operation and performing initial operability tests with bituminous coal. A preliminary evaluation of data from these tests is discussed in another paper presented at this Conference [4]. Additional tests with bituminous coal are planned in the fall of 2002 using coal from the SUFCO mine in Utah.

The transport gasifier was successfully operated on oxygen during the third gasification test campaign that was completed in June 2002. The transport gasifier operated with PRB coal in air-blown mode for about 70 hours before transitioning to enriched-air operation. The gasifier was gradually transitioned to oxygen-blown mode and operated for 150 hours. The testing verified the effectiveness of design changes to the lower mixing zone, made to achieve more uniform distribution of gas and solids and avoid localized high temperatures. Syngas heating values corrected for heat losses and nitrogen dilution effects were between 190 and 200 Btu/scf, approximately 65 percent higher than for air-blown operation.

Test results show that in-situ sulfur capture with limestone depends on the equilibrium characteristics of the syngas components rather than the amount of sulfur in the coal. When gasifying PRB coal at design conditions, the hydrogen sulfide in the syngas is relatively constant at 110 ppmv (equal to about 25 ppmv in the flue gas prior to final sulfur removal). Hence, even when processing higher sulfur coals the hydrogen sulfide content of the syngas, and hence the sulfur dioxide content of the flue gas, will remain the same.

Iron aluminide filters were extensively tested during the gasification test campaign, with the longest exposure time (2,070 hours) being in the 700 to 900°F temperature range. HTHP filter performance was acceptable, with stable baseline and peak differential pressures (Figure 6). Because of improvements made to the holders attaching the filter elements to the tube sheet, char removal efficiencies were excellent, with outlet dust loadings as low as 0.1 ppmw.

IV. COMMERCIAL DESIGN STUDY

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[3] These adjustments are made to indicate what the heating value would be from a commercial-sized gasifier. A commercial transport reactor will be larger and thus have relatively lower heat losses, will use recycled syngas for instrumentation and associated purges, and will not use nitrogen for coal conveying.

[4] Davis, B. M. et al, “Operation of the PSDF Transport Gasifier”.

A conceptual plant design and cost estimate have been completed for a commercial power plant based on an air-blown transport gasifier supplying fuel to a GE 7FA combined cycle. A simplified process flow diagram of the TRIG™ process is shown in Figure 7. Major design bases are as follows.

- Nominal 300 MW net output.
- Air-blown KBR transport gasifier.
- PRB sub-bituminous coal.
- Limestone injected into the gasifier to reduce SO_2 emissions.
- SCR in the HRSG to control NO_x.
- FGT after the HRSG to further reduce SO_2 and control SO_3, mercury, HCl, HF, trace contaminants, VOCs, and ammonia slip from the SCR unit.
- Gasifier HTHP filter operates at 700°F.
- Plant located on a greenfield site in the southeast United States.

The plant design and performance estimates are based on the data and operating experience gained from operating the transport gasifier and HTHP filter at the PSDF, and from Southern Company experience with SO_2 and NO_x control systems. Gas turbine performance calculations for the study were provided by GE Power Systems. SCS staff completed cycle analyses using commercially available software to determine the combined-cycle power output. This work, in conjunction with economic analysis, was used to identify the plant configuration with the lowest capital cost expressed in $/kW. All aspects of the work were augmented by Southern Company's design, construction and operating experience with natural gas-fired combined-cycle units.

System Description

TRIG™ Gasification Island

The gasification island for this TRIG™ design is centered around an air-blown transport gasifier, fed with nominally 140 tons/hour of PRB sub-bituminous coal. A supplemental air compressor supplies 60 percent of the process air required by the gasifier, and the balance is extracted from the gas turbine. This arrangement has two major benefits: it allows the power output of the gas turbine to be maximized at different ambient conditions by varying the relative air flow rates, and it also greatly increases the operational flexibility of the system, which is critical during startup. The air extracted from the gas turbine compressor is cooled, boosted in pressure, and regeneratively heated before it is mixed with the air from the supplemental compressor.

The gasifier converts coal, air, and steam into approximately 1,000,000 lb/hr of low-Btu syngas at 385 psia and 1,800°F. Limestone is fed to the gasifier at a design rate of 4 tons/hour and captures most of the sulfur in the coal during the gasification process. After solids removal in the disengager and cyclone, the syngas is cooled to 700°F in a fire-tube heat exchanger by raising high-pressure steam. The remaining entrained char is then removed in a HTHP filter using iron aluminide filter elements. Ninety-seven percent of the carbon in the coal is converted to syngas. The remaining carbon, together with reacted and unreacted limestone, and coal ash, (collectively termed char) is removed from the gasifier and the HTHP filters, water is added for dust suppression, and the mixture sent to landfill. Tests show that the char is non-hazardous. Combustion of the char was investigated, but the heat recovered is insufficient to justify the capital and operating cost of a dedicated combustor.

A small portion of the cleaned syngas is recycled back to the process to assist solids circulation in the gasifier and to pulse clean the HTHP filter. The remaining syngas is piped to the gas turbine. During system start-up, natural gas-fired burners heat the gasifier before solids are introduced.

The design syngas composition, by volume percent, is as follows:

CH_4	2.10	HCN	0.02
CO	19.95	H_2O	4.71
CO_2	7.46	NH_3	0.15
H_2	10.32	N_2	55.28
H_2S	0.01		

Combined Cycle Island

A GE 7FA gas turbine, modified for operation on syngas, is at the heart of the combined cycle power island. The modifications include replacing the standard dry low-NO_x combustor cans with flame diffusion combustors (to prevent flashback) and replacing the first stage of the expander to accommodate the increased mass flow associated with the supplemental air supply. The gas turbine is flat-rated on syngas at the shaft power limit (197 MW) by varying the amount of extraction air that is withdrawn as ambient conditions change.

The gas turbine uses natural gas when syngas is not available, both during gasifier outages and gasifier start-up. If natural gas is not available at a site, fuel oil can be used instead. When the gas turbine is firing natural gas, water is injected into the combustion cans to limit thermal NO_x formation. An evaporative cooling system at the gas turbine compressor inlet is used when the ambient temperature is above 65°F.

The HRSG is a single pressure unit with reheat. During syngas operation, most of the hot, high-pressure water from the economizer is routed to the gasification island steam drum. The water moves by natural circulation between the steam drum and three steam-generating coolers. Saturated steam is returned to the HRSG where it is mixed with steam from the HRSG steam drum, and then fed to the superheater sections. The final steam conditions are 1,815 psia/1,000°F/ 1,000°F. The HRSG exhaust temperature is 250°F, which is well above the acid dewpoint temperature of the flue gas. An SCR system is included in the HRSG to reduce NO_x emissions. Ammonia slip is controlled in the SCR to minimize ammonium bisulfate production.

The HRSG is integrated with the gasification island in three additional ways. First, a small process steam flow for the gasifier is extracted from the cold reheat line. Second, the discharge of the condenser is routed through the gasification island, where it is used for low level solids and gas cooling and compressor intercooling. Third, the HRSG provides high-pressure steam to drive the supplemental air compressor.

Wet steam from the supplemental air compressor steam drive exhaust is combined with wet steam from the main steam turbine exhaust and condensed at 1.5 inches of mercury absolute by water from the mechanical draft cooling tower.

When the gasification island is not operating, the HRSG alone must raise all of the high-pressure steam. In this mode of operation, a duct burner upstream of the HRSG evaporator section fires natural gas to boost steam flow and pressure. The HRSG also has a natural gas-fired duct burner upstream of the last superheat section for peaking operation.

Coal and Limestone Feed Systems

The design coal is PRB sub-bituminous with the following average as-received ultimate analysis:

	Weight Percent		Weight Percent
Carbon	51.75	Sulfur	0.26
Hydrogen	3.41	Ash	5.13
Nitrogen	0.71	Moisture	27.21
Oxygen	11.53		
Higher heating value (Btu/lb)	8,760	Lower heating value (Btu/lb)	8,240

The raw coal is delivered to the site at a rate of 24,000 tons per week by two trains consisting of bottom-dump, rapid-discharge rail cars. A radial pedestal stacker conveyor is used to form a kidney shaped coal pile with a capacity of 100,000 tons, equivalent to 30-days of live storage at the design feed rate. The stack can be extended to allow up to 15 days of dead storage.

For reliable operation the gasifier has four coal preparation and feed systems, three of which are in service at any time with the fourth on standby. The plant prepares 245,000 lb/hr of coal with a top size of 700 microns. The pulverizers are roll-mill crushers that incorporate a flash dryer using a hot gas at 430°F to dry the coal to approximately 18-percent moisture. The drying gas is heated in shell-and tube exchangers using intermediate pressure steam. Steam heating is preferred as it avoids the operating cost associated with fuel-fired burners. It also minimizes the amount of moisture present in the drying gas and improves drying efficiency.

Each of the four coal-feed systems to the gasifier consists of a surge bin that receives the prepared coal, a lock vessel, a feed vessel, and a rotary feeder with a vertical axis. Each feeder is controlled by a variable speed drive with a 5-to-1 turndown ratio. The coal is transported into the gasifier via the air stream of a dilute-phase conveyor. Each system is designed to feed 33 percent of the total design coal flow with a 10-percent margin.

The limestone used in the design has the following average as-received ultimate analysis:

	Weight Percent
$CaCO_3$	79.8
$MgCO_3$	5.0
Ash	5.2
Moisture	10.0

The limestone is delivered to the site at a rate of 640 tons per week, which requires around 6 truck loads per day. These trucks dump directly onto a 15-day storage pile. From this pile, the limestone is conveyed into a milling and drying system almost identical to that for the coal. There are two parallel limestone preparation systems, each with a capacity of 110 percent of the design feed rate. The prepared limestone top size is 500 microns. Both prepared limestone surge bins have a side off-take port with a rotary valve to gravity feed limestone to the FGT limestone slurry preparation tank.

Plant Performance

Projected performance data for the TRIG™ plant operating on syngas and on natural gas at ambient conditions of 65°F and 60 percent relative humidity are shown in Table 1.

Table 1. First-of-a-Kind TRIG™ Plant Performance

	Syngas	Nat. gas	
Power Output			
Gas Turbine, Gross	197	168	MW
Steam Turbine, Gross	118	118	MW
Auxiliary Load	18	8	MW
Net Plant Output	297	278	MW
HHV Heat Rate and Efficiency			
Heat Input From Coal	2,420		MBtu/hr
Heat Input From Natural Gas		2,160	MBtu/hr
Net Heat Rate	8,130	7,790	Btu/kW-hr
Net Efficiency	42.0	43.8	%
LHV Heat Rate and Efficiency			
Heat Input From Coal	2,280		MBtu/hr
Heat Input From Natural Gas		1,940	MBtu/hr
Net Heat Rate	7,680	7,020	Btu/kW-hr
Net Efficiency	44.4	48.6	%

Even for this Serial No. 1 plant the heat rate on syngas, 7,680 Btu/kW-hr, LHV (44.4 percent efficiency), is better than that of currently available coal-based power plant technologies. Because the gas turbine is modified to use syngas, the LHV heat rate when fired on natural gas, 7,020 Btu/kW-hr (48.6 percent efficiency), is higher than that of currently available natural gas-fired combined cycles. However, this mode of operation increases the TRIG™ system availability, which is especially important during peak load times.

An estimate of the emissions for the major regulated species is presented in Table 2

Table 2. Projected Emissions from a TRIG™ Plant

	lb/MBtu	ppmv (*)	lb/MWh
NO_x	<0.05	<12	<0.40
SO_2	<0.005	<1	<0.04
Particulate	<0.0003	<0.20	<0.002

(*) particulate presented as ppmw

In addition, the proprietary FGT unit removes almost all the remaining environmental species of interest, including sulfur trioxide, hydrogen chloride, hydrogen fluoride, ammonia slip from the SCR unit, oxidized and nonoxidized mercury, trace elements, and volatile organic compounds to near their lower detection limits. When built, the TRIG™ plant will be the cleanest, and when adjusted for local conditions, the most efficient coal-based power plant technology in the world.

Economic Evaluation

Capital Costs

The capital cost includes estimates for equipment, labor, materials, indirect construction costs, engineering, contingencies, and land. Land is valued at $3,200 per acre. Sales tax is 5 percent and freight is 2 percent of the equipment cost. An overall contingency factor of 10 percent is applied to the estimate. Cost estimates were developed using commmercial power plant costing software, process plant costing software, vendor quotes, and historical Southern Company cost information.

The capital costs are assembled into the categories of a Southern Company standardized work breakdown structure:

- Indirects -- engineering and environmental services, project management, construction management, temporary facilities and services, production costs, builder's risk insurance, ad valorem taxes, and land
- General Site -- site preparation, site infrastructure, and non-process buildings
- Steam Generation -- HRSG with SCR
- Turbine and Generator -- gas turbine, steam turbine, condensate system, and feedwater system
- Fuel Facilities -- coal unloading and reclaim, coal and limestone preparation and feed, gasifier process equipment, gasifier island steel structure, natural gas delivery, and fuel handling fire protection
- Emission Facilities -- HTHP filter, limestone reclaim, FGT equipment, exhaust gas stacks, and char handling and disposal

- Plant Water Systems -- cooling water supply, cooling tower, condenser, service water system, water treatment and condensate makeup, and wastewater treatment system
- Electrical Distribution and Switchyard -- bulk cabling and wiring, A.C. systems, emergency generator system, generator bus system, and switchyard
- Plant Instrumentation and Controls -- local racks and panels, monitoring and control systems, control consoles, and water analysis systems
- Other -- sales tax and freight, contractor management, contingency, and other miscellaneous costs

Costs were developed both for first-of-a-kind and second-of-a-kind 1-on-1 300-MW TRIG™ plants. The first-of-a-kind cost includes items such as increased engineering and additional startup requirements that put the technology at an economic disadvantage. These and similar costs were adjusted to identify the costs for the second-of-a-kind unit. The capital costs resulting from this evaluation are summarized in Table 3. The total plant cost [5] for this second-of-a-kind 300-MW TRIG™ system is estimated to be $411.3 million ($1,385/kW). The costs are broken out by major functional area in Figure 8. A preliminary three-dimensional view of the power island for the plant is shown in Figure 9.

Table 3. Total Plant Cost Summary for Second-of-a-Kind TRIG™ Plant

Account	Cost in $million	$/kW
Indirects	72.5	244
Site, General	17.7	60
Steam Generation Area	25.5	86
Turbine & Generator Area	59.8	201
Fuel Facilities	104.3	351
Emission Facilities	31.2	105
Plant Water Systems	20.2	68
Electrical Distribution & Switchyard	18.1	61
Plant Instrumentation & Controls	5.6	19
Other	56.4	190
Grand Total	411.3	1385

A 1-on-1 combined cycle configuration was chosen to evaluate investment options while limiting the total installed cost and financial risk for a first-of-a-kind TRIG™ plant. The 300-MW module allows scale up to larger, more economical sizes with no risk. For example, a nominally 600 MW 2-on-1 configuration consists of two 300-MW gasifier trains including the same equipment as that proven at the 300-MW scale. The second-of-a-kind costs for the 300-MW unit were adjusted for economy-of-scale and by using historic cost reduction profiles to produce the cost for an

[5] This includes all expenses except the cost of capital during construction and startup costs.

nth-of-a-kind 600-MW unit. This gives a total plant cost estimate of $1,040/kW for a TRIG™ plant using similar components to those incorporated in the 300-MW plant.

A major incentive for commercializing this technology is the potential to build future plants around H-class gas turbines. Their high output and efficiency can enable the construction of clean, relatively simple coal-fired power plants that have efficiencies well over 50 percent (LHV) with total plant costs of near $1,000/kW [6] for a 1-on-1 configuration. Projected cost and performance for a first, second, and nth TRIG™ plant are shown in Figure 10.

Comparison with Other Coal-Use Technologies

To quantify the potential advantages of the TRIG™ technology, the projected thermal performance and costs for an nth-of-a-kind plant were compared with those of other coal-based power plant technologies given in EPRI's 2001 Technical Assessment Guide (TAG™). The details behind this information are not all publicly available. The following technologies were selected:

- A Shell oxygen-blown IGCC plant based on two gasifiers supplying two GE 7FA gas turbines, full heat recovery, methyl di-ethanolamine (MDEA) sulfur removal, and 1,615 psia/1,000°F/1,000°F steam conditions.
- An E-GAS™ (formerly Destec) oxygen-blown IGCC plant with a similar specification to the Shell plant.
- A Texaco oxygen-blown IGCC plant based on two gasifiers supplying two GE 7FA gas turbines, syngas quench, MDEA sulfur removal, and 1,415 psia/1,000°F/1,000°F steam conditions.
- A supercritical PC plant with SCR and FGD, and 3,515 psia/1,050°F/1,050°F steam conditions.

Because the plant sizes are different and have different economies of scale, the costs were normalized to 500 MW using the TAG™ procedure. The following economic parameters were used to calculate the levelized cost of electricity, in constant dollars, for these technologies:

- Fuel cost [7] is $1.25/MMBtu with annual escalation of -1.03 percent
- Plant book life is 20 years
- Capacity factor is 80 percent
- Carrying charge factor is 0.142
- Costs are in mid-2001 dollars

Because of projected thermal improvements, the 600-MW TRIG™ plant is expected to have an efficiency of 46.0 percent (LHV), or a heat rate of 7,420 Btu/kWh (LHV)

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[6] *Market-Based Advanced Coal Power Systems, Final Report*, Office of Fossil Energy, U.S. Department of Energy, Washington, DC, November 1999.

[7] Fuel cost is the average for the United States and is taken from *Annual Energy Outlook 2001*, Energy Information Administration, Washington, DC, December 2000.

Table 4. Comparison of 500-MW Coal-Based Power Plant Technologies

	n^{th}, TRIG™	Shell	E-GAS	Texaco Quench	PC
Plant Performance					
Heat Rate, Btu/kWh, LHV	7,420	7,930	7,950	9,020	8,130
Efficiency, LHV	46.0	43.1	43.0	37.9	42.0
CO_2 emissions, lb/MWh	1,600	1,710	1,720	1,940	1,750
Plant Costs					
Total Plant Cost*, $/kW	1,100	1,350	1,170	1,160	1,070
Fixed O&M, $/kW-yr	19.8	39.4	35.0	36.5	27.5
Variable O&M, $/MW-hr	3.1	2.2	2.2	2.2	2.8
Levelized Costs					
Capital, cents/kW-hr	2.23	2.74	2.37	2.35	2.17
O&M, cents/kW-hr	0.59	0.78	0.72	0.74	0.67
Fuel, cents/kW-hr	0.90	0.94	0.94	1.07	1.02
COE, cents/kW-hr	3.72	4.46	4.03	4.16	3.86

*Adjusted using the formula $TPC_1 = TPC_2 (MW_2/MW_1)^{0.245}$

The power plant costs from EPRI TAG™ are only available for Illinois No. 6 bituminous coal not the sub-bituminous coal used for the TRIG™ plant cost estimate. EPRI data suggest that any error introduced by this difference is small.

The results are summarized in Table 4 and Figure 11. The Total Plant Cost for the n^{th}-of-a-kind TRIG™ plant is lower than the three IGCC plants and almost the same as the supercritical PC plant. The heat rate, coal consumption, O&M costs, and cost of electricity are all much lower for the n^{th}-of-a-kind TRIG™ than for the other four plants.

V. FUTURE RESEARCH PLANS

NETL, Southern Company, and other participants are currently planning the next five years of research at the PSDF. The main goals are to support DOE's Vision 21 program for developing the next generation of power plants and to support commercialization of an air-blown transport gasifier-based power system. Major proposed activities for 2002 through 2006 include the following:

- continue air-blown and oxygen-blown gasification development
- integrate oxygen-blown gasifier with advanced air separation technology
- integrate gasifier with existing combustion turbine at the PSDF
- evaluate multi-contaminate (H_2S, Hg, HCl, etc.) controls

- evaluate novel CO_2 and H_2 separation systems
- test advanced materials in gasifier and CT test section
- evaluate high temperature gas and particle sensors
- improve system integration and controls
- improve gas cooling technology
- improve coal and limestone feed systems and ash cooling systems

VI. CONCLUSIONS

A coal-fired transport gasifier-based power plant that includes a HTHP filter holds promise for near-term commercialization, based on test results at the PSDF. Approximately 5,000 hours of combustion and over 2,700 hours of gasification tests have been completed with excellent performance.

A commercial design study of the Transport Reactor Integrated Gasification (TRIG™) combined cycle shows that a first plant will encounter typical first-of-a-kind problems of high capital and operating costs. However, subsequent plants are expected to be competitive with other coal-based power systems even before the full potential of a plant based on H class gas turbine technology is reached.

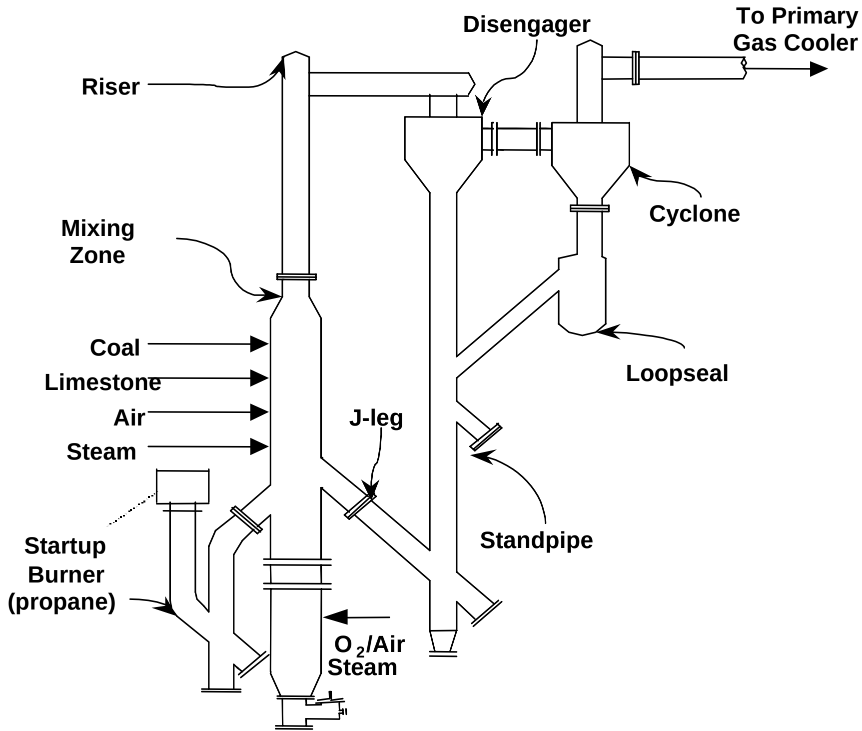

Figure 1. Transport Gasifier

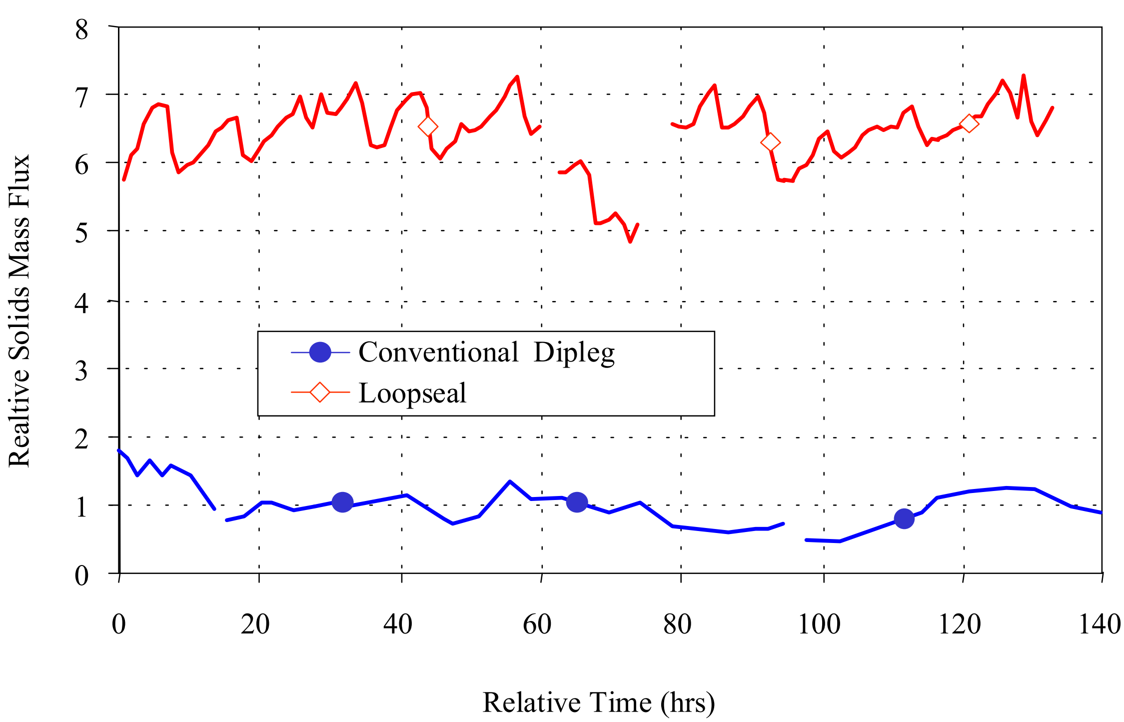

Figure 2. Relative Solids Mass Flux in Gasifier Before and After Loop Seal Addition

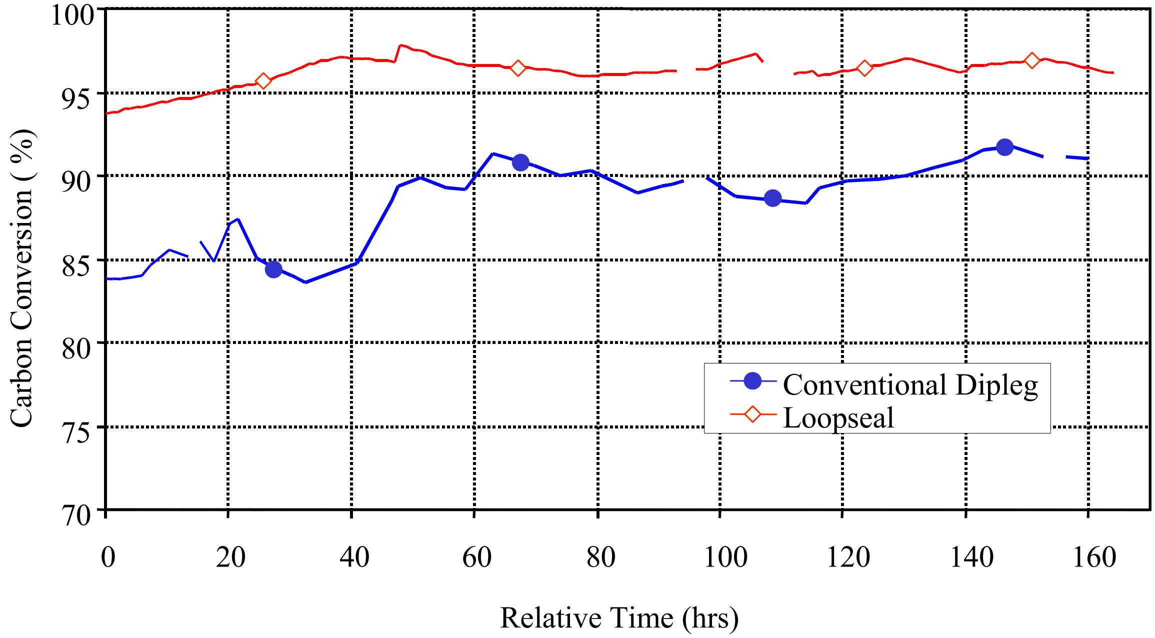

Figure 3. Carbon Conversion Before and After Loop Seal Addition

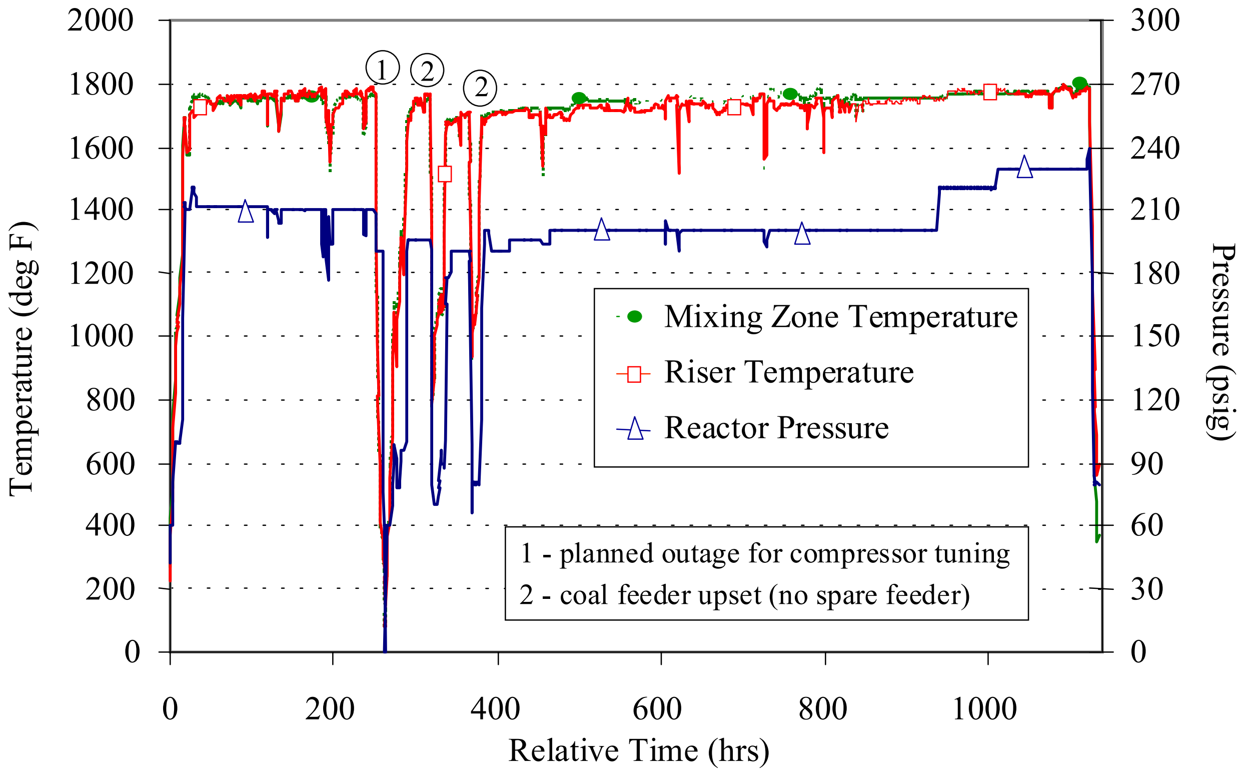

Figure 4. Gasification Test Campaign Temperature and Pressure Data

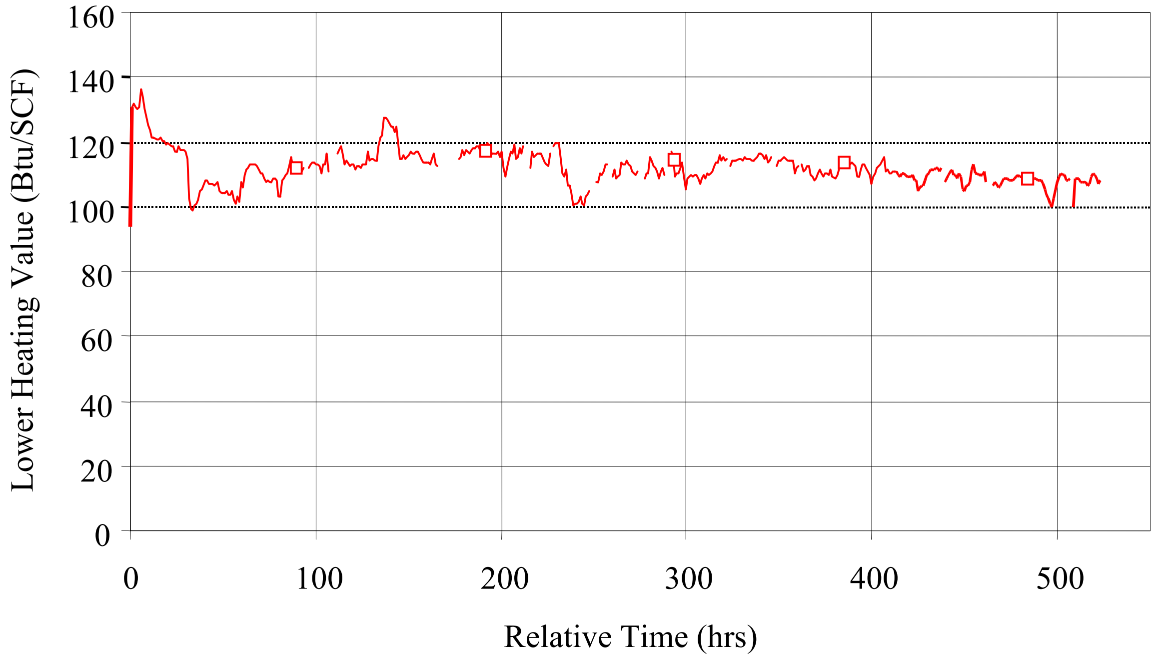

Figure 5. Gasification Test Campaign Syngas Heating Value

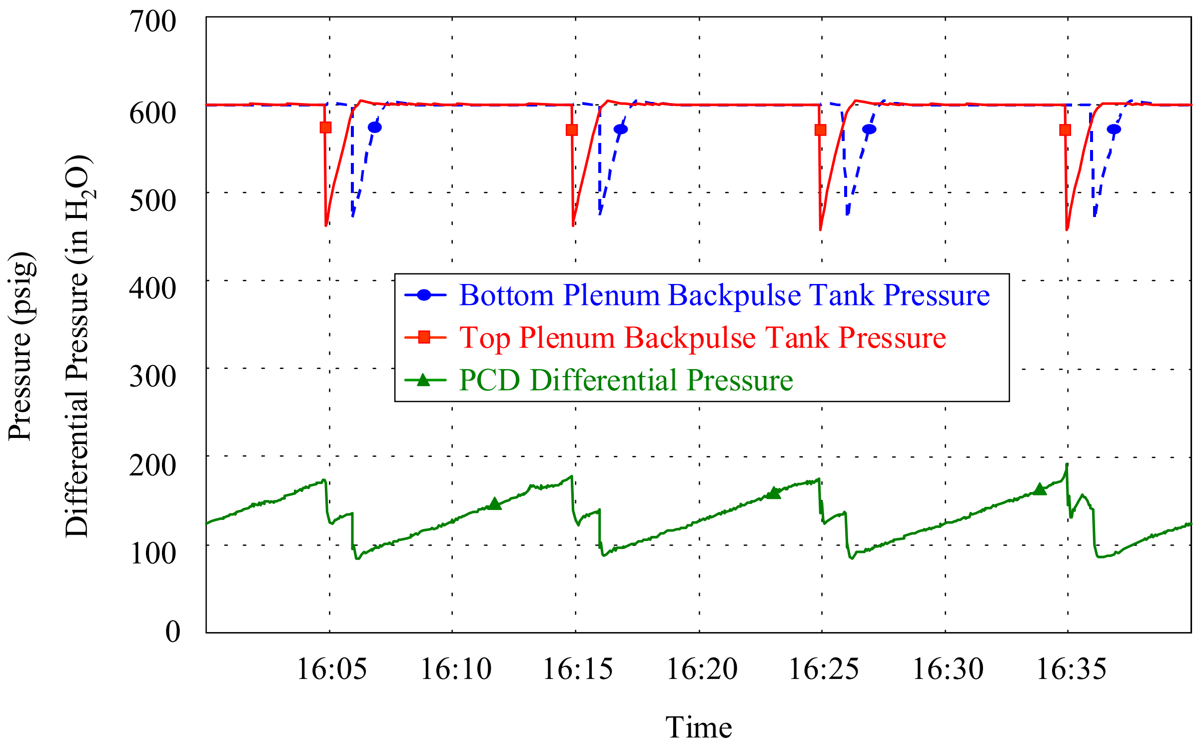

Figure 6. Typical Backpulse Tank Pressures and HTHP Filter Differential Pressure

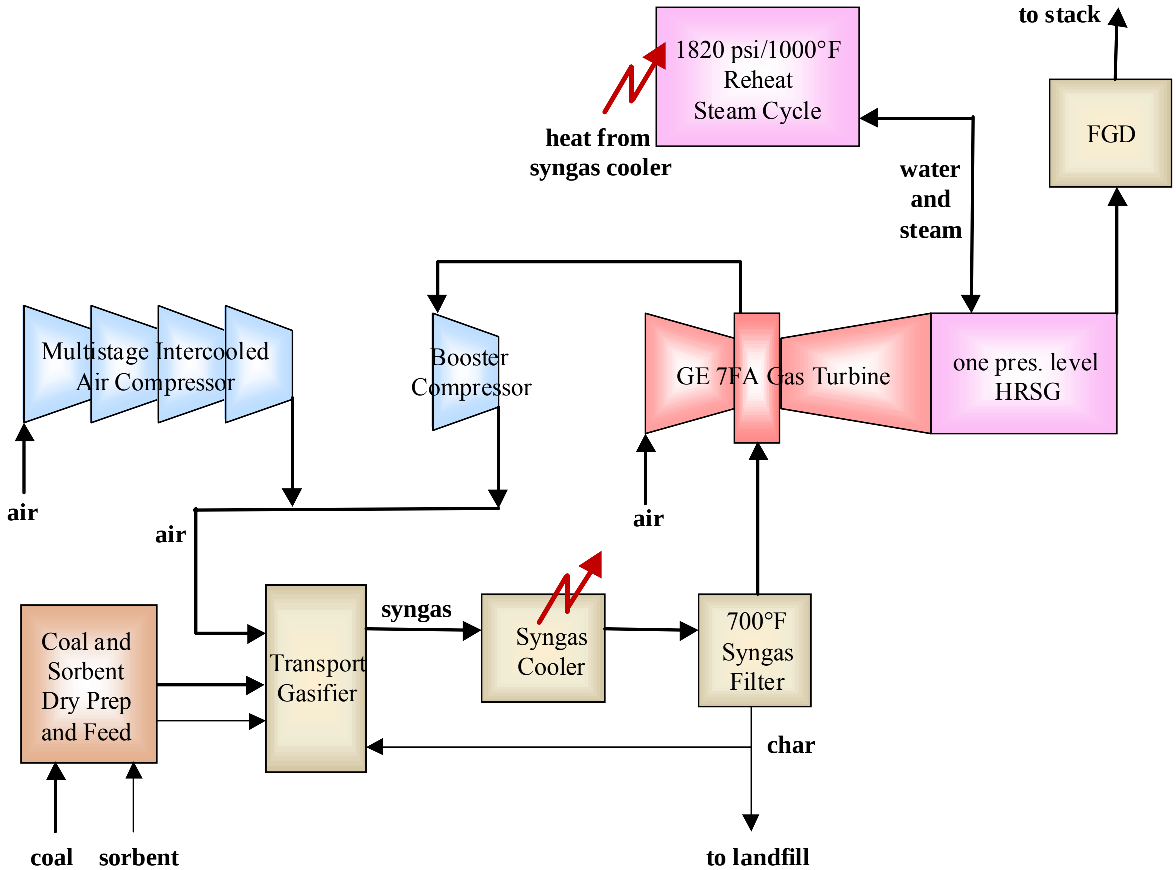

Figure 7. Simplified TRIG™ Process Flow Diagram

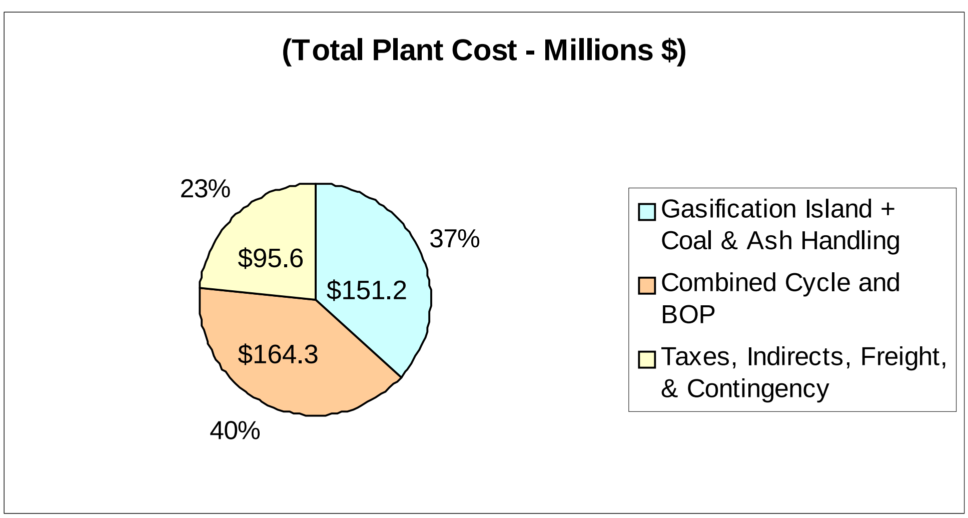

Figure 8. Serial No. 1 TRIG™ Capital Costs Broken Out by Major Functional Area

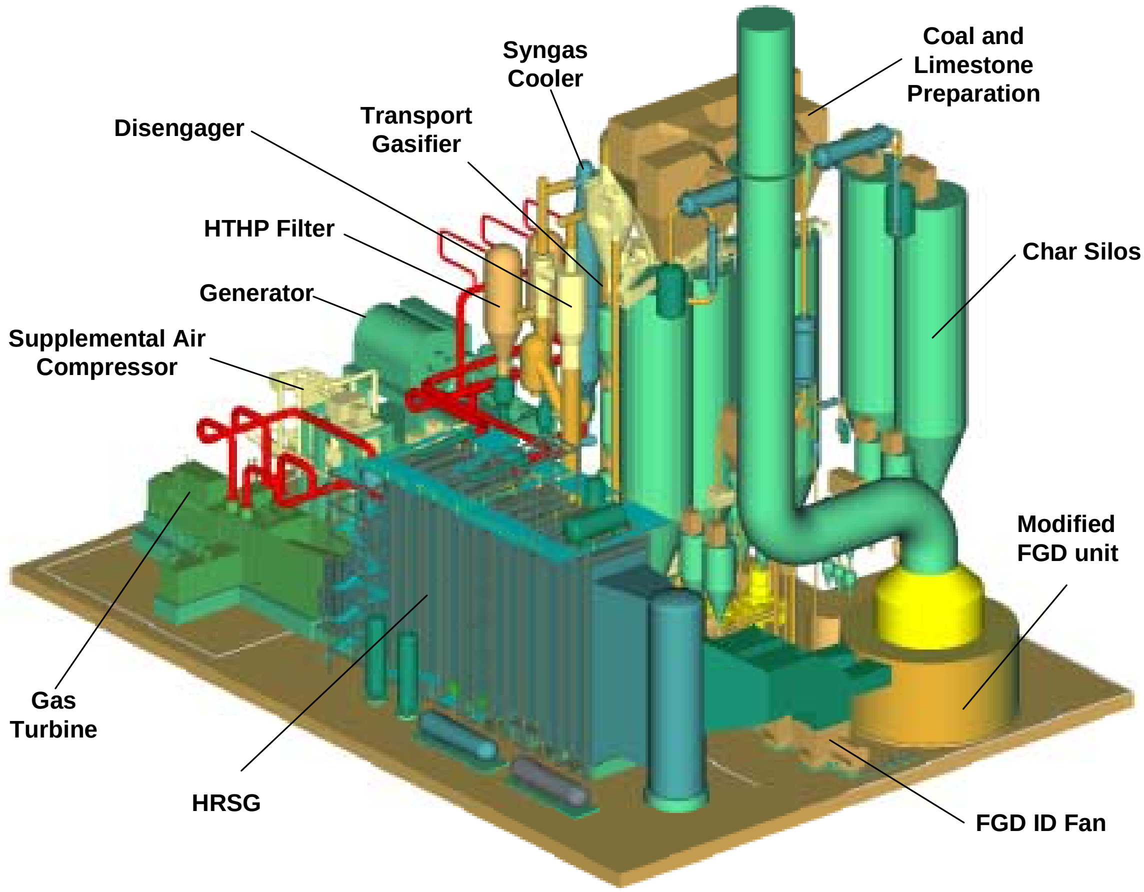

Figure 9. Three-Dimensional View of Power Island

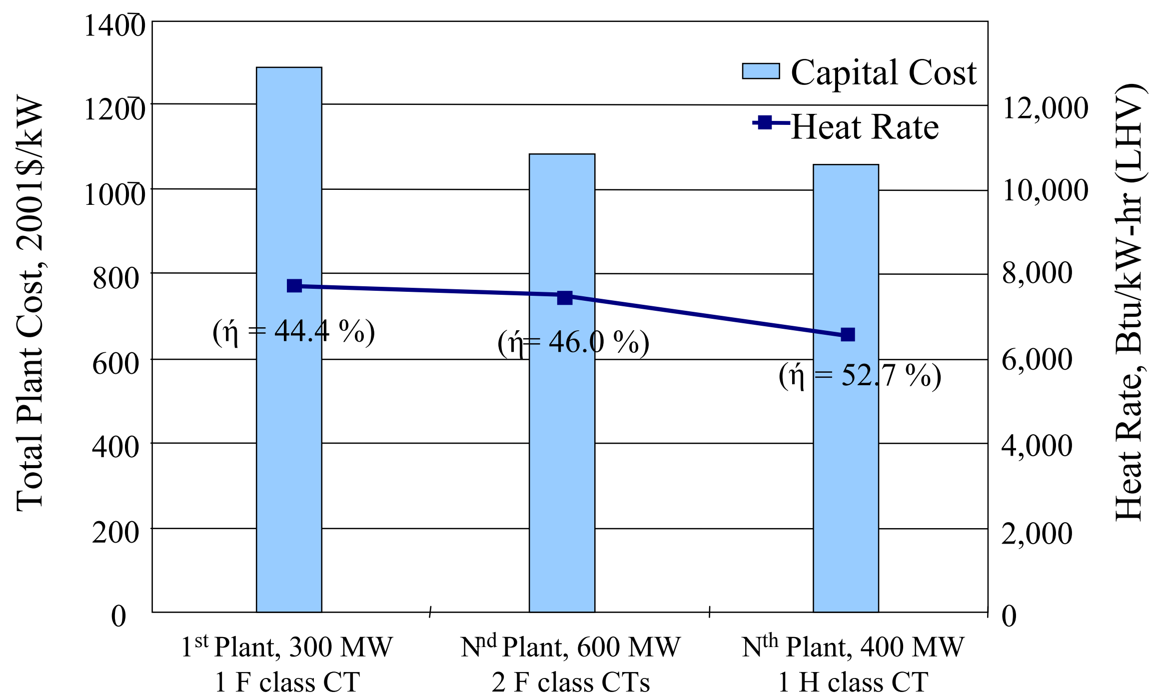

Figure 10. Projected TRIG™ Cost and Performance Improvements With Subsequent Plants

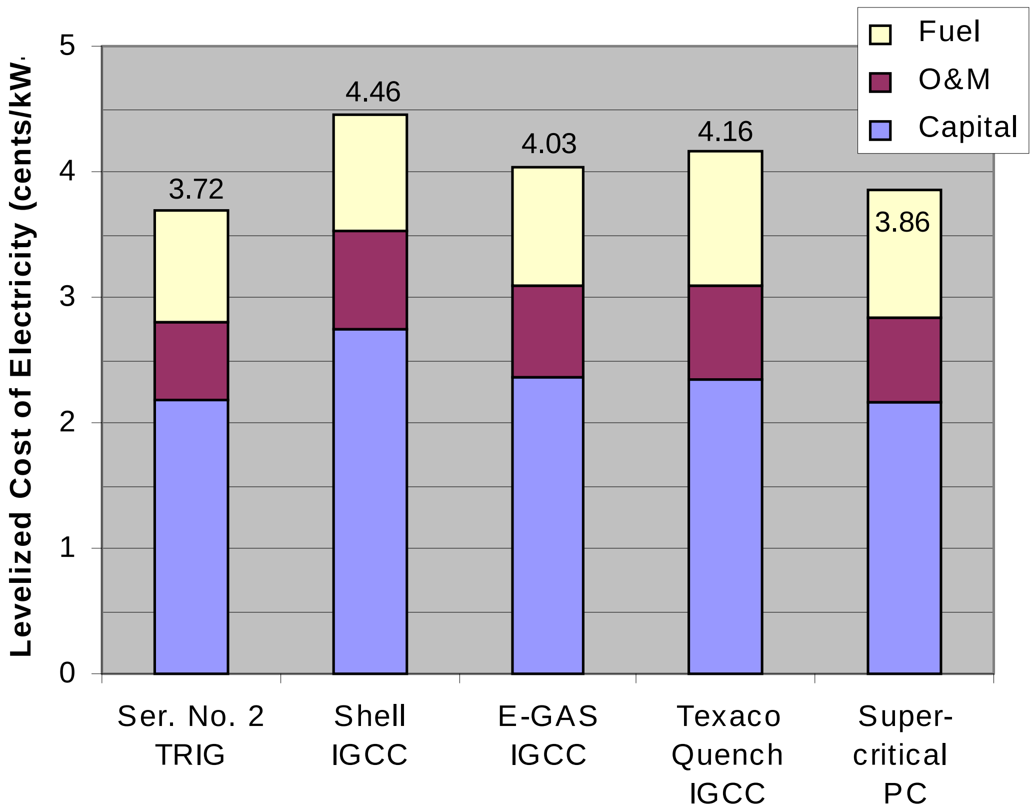

Figure 11. COE Comparison with Coal-Use Technologies from EPRI TAG™